Harness sizing approach for bundles equipped with EMI shields

4TH SPACE PASSIVE COMPONENT DAYS

DEFENCE AND SPACE

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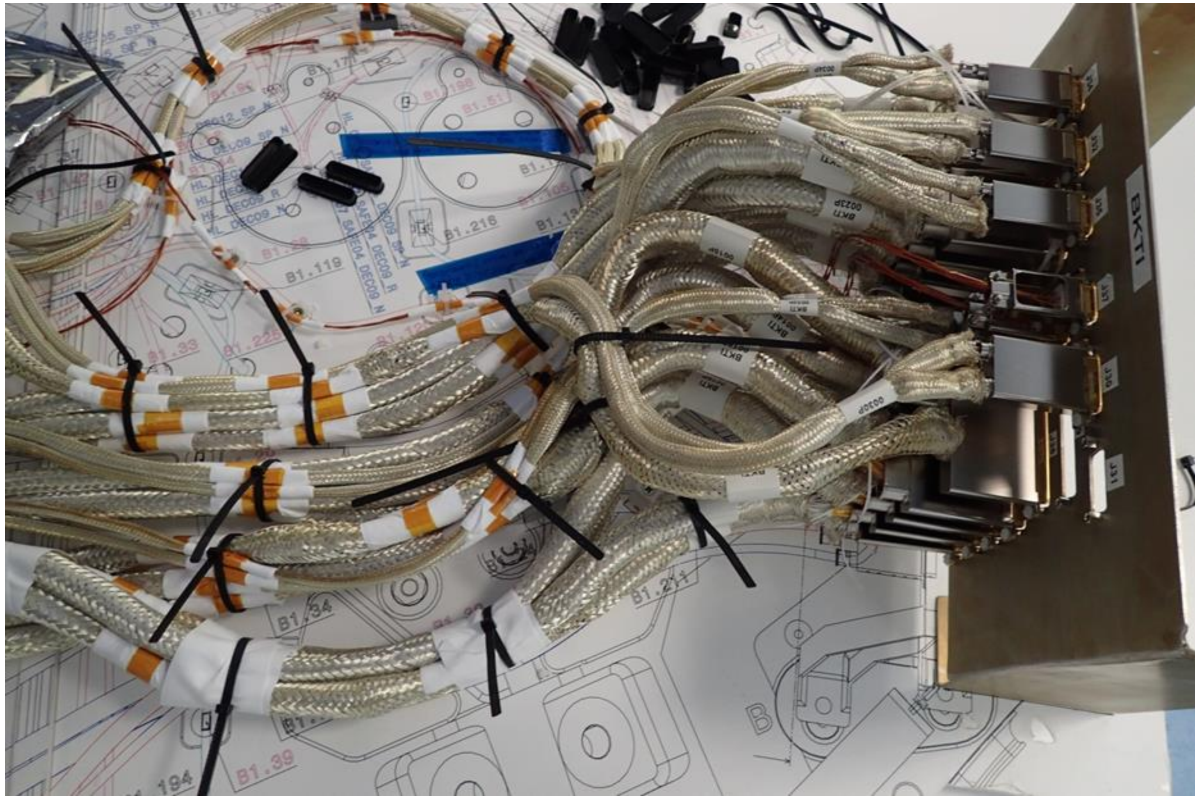
AIRBUS

Space Harness Optimization

Mass and Volume are critical in Space.
The Harness mass can exceed 250kg, some bundle diameters may exceed 50 mm, made of hundreds of wires.

For the power harness, the sizing of the conductors is mainly driven by the maximum temperature of the wires resulting from:

- The self heating induced by the electrical current running into the wires (resistive power losses).
- The thermal exchanges with the environment.
- The thermal exchanges between the wires within a bundle.



Space Harness Optimization

In 2016, ESA proposed a 2-year project with the following goals:

- To upgrade the sizing rules taking into account most of the sizing drivers, with easy methods and clear justifications.
- To make possible further harness design optimization through simulation for complex use cases (e.g. partially loaded bundles).

This study was granted to conducted by Airbus Defence and Space and the NLR. It included a test campaign covering various samples and hundreds of thermal vacuum and electrical current conditions, as well as the development of thermal models for wires and bundles.

The project was successfully completed and the results, presented in SPCD 2018, resulted a major update of the derating rules for wires and cables in the standard:

“Space product assurance - Derating - EEE components”, ECSS-Q-ST-30-11C Rev 2, formally issued in June 2021.

This paper presents an extension of that study related ElectroMagnetic Interference (EMI) shields implemented on some on of the harness bundles.

Space Harness Sizing: ECSS-Q-ST-30-11C Rev.2

The new ECSS derating rule proposes:

– A formula to compute the allowable current (i.e. ampacity) in a single wire, using all relevant parameters

$$I_{SW} = \sqrt{\frac{\varepsilon \cdot D \cdot \pi}{R_{Tref}}} \times \sqrt{\frac{\sigma\left(T_{wire}{}^{4} - T_{env}{}^{4}\right)}{1 + \alpha\left(T_{wire} - T_{ref}\right)}}$$

where:

I_{SW}	=	Single wire current for the considered wire gauge [A]
α	=	Stephan-Boltzman constant = 5,67 E10-8 [W /(m² K⁴)]
T_{wire}	=	Effective wire temperature [K]
T_{ref}	=	Reference temperature for the resistance (for example 293,15 K or 20 °C [K]
T_{env}	=	Temperatures of the environment considered as a black body [K]
R_{Tref}	=	Ohmic resistance (ohm/m) at T_{ref} (for example at 20 °C as previously considered) [Ω/m]
C_t	=	Coefficient of temperature for the wire resistance [K^{-1}]
ε	=	Thermal Emissivity of the wire's surface [-]
D	=	Wire's external diameter [m]

– An additional factor to multiply with the above current in order to consider the thermal conduction between the wires within the bundle, depending on the count of wires (assuming all wires are fully loaded):

Count of wires		1	2	3	4	5	6	7	8	9	10	15	25	50	100	200	300
Bundle derating factor		1	0,9	0,81	0,76	0,71	0,66	0,62	0,6	0,59	0,57	0,49	0,4	0,29	0,21	0,15	0,12

Ampacity of a wire in the bundle:

$$I_{BW} = I_{SW} * K(N)$$

With:
IBW = Sizing Current for wire in bundles for the considered wire gauge [A]
N = the count of wires in the bundle
K (N) = The bundle derating factor given by this table.

Limitations, Extension of the Study

The scope of the initial study could not cover all of the harness configurations we can use in space (quite infinite).

One of the significant exclusion was related to **bundles covered with ElectroMagnetic Interference shields**, although it was expected that shielding sleeves could have a significant detrimental impact on the thermal behaviour of the bundle. This had been confirmed by thermal tests previously performed by Airbus Defence and Space on specific bundles.

Therefore, ESA and Airbus DS decided to co-finance an extension of the study to investigate the impact of bundle EMI over-shields on the allowable electrical current.

ECSS-Q-ST-30-11_0140214

b. The following formula may be used to rate the maximum current in a single wire (ISW), specified in requirement 6.32.4a in vacuum, for an environment temperature of T_{env} environment, to reach a wire surface temperature of T_{wire}, providing the following conditions are met:

1. the radial thermal gradient between wire outer surface and the inner conductor core is insignificant under nominal currents and can therefore be neglected:

   $T_{wire} \approx T_{cond} \approx T_{diel}$

   where

   T_{wire} = Effective wire temperature [K]

   T_{cond} = Conductor temperature [K]

   T_{diel} = External temperature of the wire's dielectric [K]

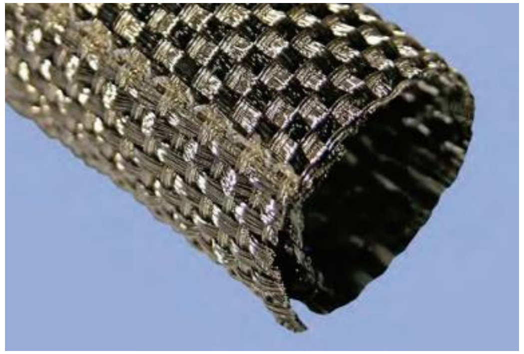
2. the heat transfer along the axis of the conductor can be neglected (i.e. there is no significant temperature gradient along the wire)
3. the dielectric is fully opaque e.g. the absorptivity equals 1
4. no external radiative source are present (e.g.: no solar flux), the absorptivity of the environment considered as a black body is supposed to be equal to 1
5. no overshields or braids are applied.

$$I_{SW} = \sqrt{\frac{\varepsilon . D . \pi}{R_{Tref}}} \times \sqrt{\frac{\sigma({T_{wire}}^4 - {T_{env}}^4)}{1 + C_t(T_{wire} - T_{ref})}}$$

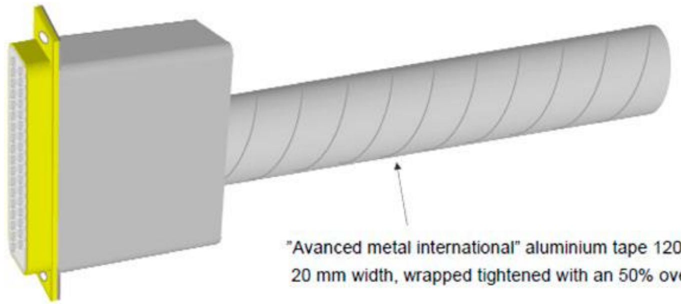
Scope

The extension of study intended to evaluate the effect of bundle EMI over-shield on the ampacity of the wires.
Two very common types of shields have been investigated:

- Nickel plated copper braid
  Federal Mogul
  Roundit® FMJ sleeve



- Aluminium foil wrapping, one and two layers
  Advance Metal International
  Aluminium tape 20mm width,
  wrapped tightened, 50% overlap



The effect of additional polyimide and PTFE tape wrapped around the shielded bundles was also investigated.

Methodology

- **Step 1 : Test campaign**
  The thermal impact of the over-shields was evaluated by comparing the results of this test campaign with the results obtained on the same bundles without over-shields, in the same environment conditions, during the previous test campaign. The approach was to evaluate the reduction of current needed in the EMI-shielded bundle to reach the same worst-case wire temperature obtained in the un-shielded bundle.

- **Step 2: Thermal model implementation and correlation**
  Based on the generic thermal model of bundles implemented by Airbus Defence and Space for the previous study, specific models were developed for both types of shields. The parameters of the models were correlated with the test results.

- **Step 3: Analysis and Outcomes**
  The test results and the thermal models have been used to evaluate the effect of the shields on the ampacity of the wires.

Test Campaign

The tests performed in the former study established the current loads to be injected in different types of bundles, in different environment of temperature (in vacuum) to reach pre-defined wire temperatures in the core of the bundle.

The objective of the present tests was to identify the reduction of these current loads needed to reach the same core temperature in the same conditions after implementing EMI over-shields on the same bundles.

Using the same test sequences, the same samples and the same NLR test facilities made the test measurements of both test campaigns fully comparable.

Test samples

Bundle #	Number of wires	Type	Gauge (AWG)	Standard	Number of current groups
B3	14	Single wires	20	3901/002	2
B5	100	Single wires	20	3901/002	3
B6	200	Single wires	20	3901/002	3

Test Conditions

Environment Pressure	Environment (Shroud) Temperature (± 5°C)	Target cable bundle temperatures (± 5°C)
High vacuum ($<10^{-5}$mbar)	25°C	75, 150 °C
High vacuum ($<10^{-5}$mbar)	100°C	125, 150 °C

Test setup

Bundles installed in the vacuum chamber at NLR – Photo courtesy of NLR

Test Results

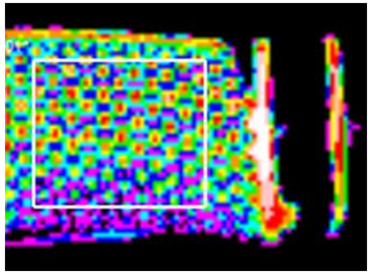
- Effect of nickel-plated EMI braid (Roundit® FMJ)
  The electrical current loads had to be reduced by 20 to 33% (meaning a reduction of 36 to 54% of the thermal dissipation) to reach the same maximum wire temperature as the unshielded ones.
  The addition of PTFE wrapping (Celloflon®) on top of Nickel-plated EMI Braid improved a little bit the thermal exchanges, leading to an increase of the electrical current from 5 to 10%.

- Effect of one Layer of Aluminium Foil
  The electrical current loads had to be reduced by 47 to 71% to reach the same maximum wire temperature as the unshielded ones.
  The addition of a second layer of Aluminium foil did not have much impact on these figures.
  The addition of polyimide on top of the aluminium foil improved significantly the thermal exchanges, leading to an increase of the electrical current from 60 to 80% compared to the above, resulting in a net reduction of the current loads of around 50% worst case.

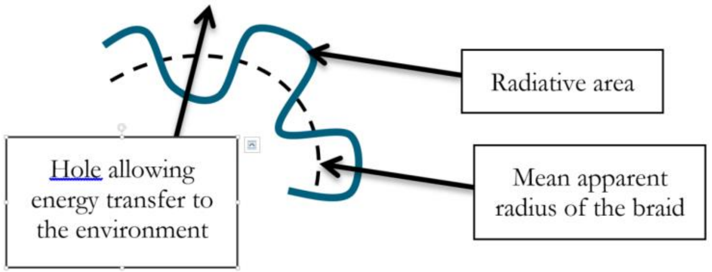
Mathematical Model for Nickel-Plated Copper Braid

The shielding braid used during the test has two geometrical characteristic that influence the way the thermal energy is transferred between the cables behind the braid and the environment:

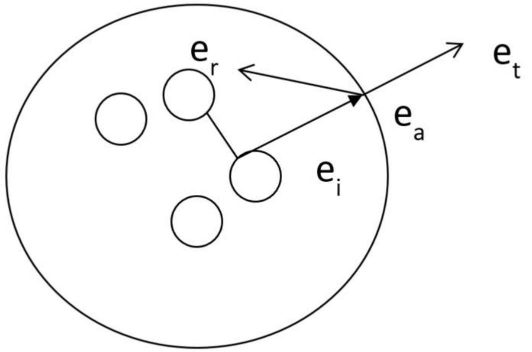
- The transparency of the braid: some holes allow direct radiative exchanges from the cable surface to the environment.
- The radiative area of the braid, which cannot be modelled as a perfect cylinder because of the holes.



Infrared picture of the braid



Geometrical representation of the shielding braid



$$e_i = e_a + e_t + e_r$$
$$e_a = \varepsilon e_i$$
$$e_t + e_r = (1 - \varepsilon) e_i$$
$$e_t = \tau(1 - \varepsilon) e_i$$
$$e_r = (1 - \tau)(1 - \varepsilon) e_i$$

Where:

ε *is the absorptivity in the IR length of the shielding braid*

τ *is its transparency coefficient*

e_a *is the absorbed radiative energy (by the braid)*

e_t *is the transmitted energy (to the environment)*

e_r *is the reflected energy.*

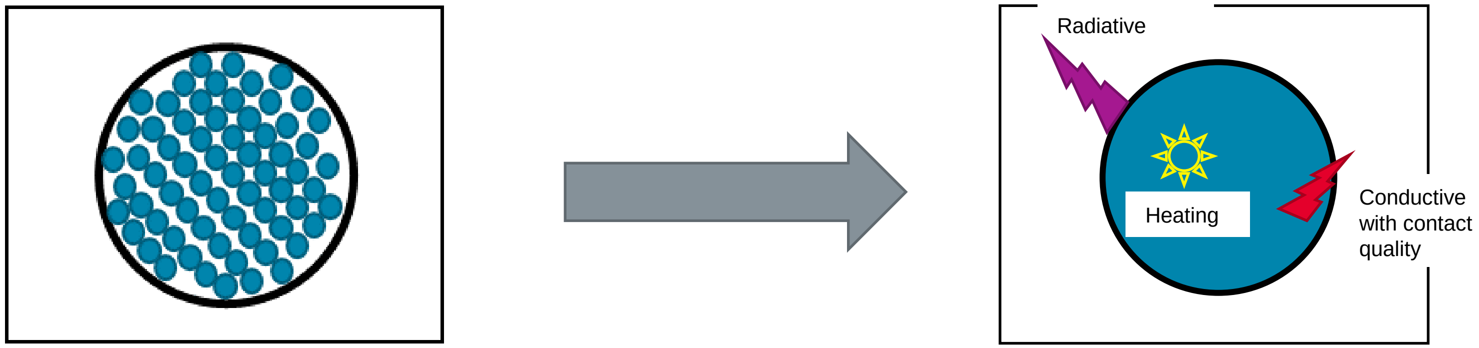
Energy balance during ray tracing: introduction of transparency

The ray propagation is stopped once the reflected energy is small enough

Mathematical Model for Aluminium Wrapping Shield

With aluminium wrapping, the test have shown that the temperature gradient between the cables is small. The explanation of this quasi-homogeneous temperature inside the bundle is ascribed to the low emissivity/absorptivity of the aluminium surface.

The problem was therefore reduced to a simpler one, with one node representing the bundle temperature (one cable, ie the common cables temperature), and one node representing the aluminium foil.
To model the fact that the wrapping is not perfect, in the sense that the conductive contact is irregular between the cables and the aluminium foil, a contact quality coefficient has been introduced reducing the conductive coupling

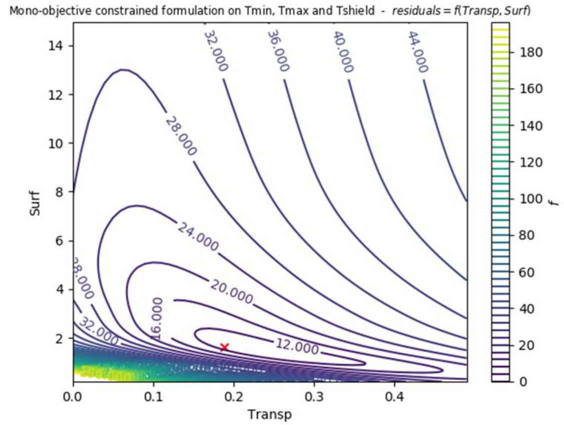


Key Findings on Modelization

- The correlations done in the frame of this study have been quite successful, but they had to be limited to the configurations described above.

- The impact on the derated current estimation is highly dependent on the EMI shielding itself:
  Each EMI-shielding technology may deserve specific tests, and possibly specific modelling.
  If the mathematical models presented here contain some part of generality, the correlation shows that it may lead to several parameters to adjust in order to get a “universal” model. Two kind of approaches are of importance: physical and mathematical modelling on one side, bread boarding and tests on the other side.
  Therefore, additional modelling efforts are still needed to improve our understanding and our capability to support the current sizing of the wires in any shielded bundle.

- On the mathematical modelling process, the interest of using data science techniques (methodology, tooling and pre-existing on the shelf framework) during the correlation was demonstrated here, with a clear benefit.



Example of Surrogate model used during model correlation

Simulation

The simulations allowed to compute the Shielding Derating Factor in several conditions:

- Different gauges: AWG12, AWG16, AWG20, AWG24
- Different environment temperature: 40°C and 80°C
- Different numbers of wires in the bundle: 10, 25, 50, 100, 200

The target wire temperature was set to 150°C, which is the maximum derated temperature applicable to the most common wires used in space applications.

Application: Introduction of a ‘Shielding Derating Factor’

A new factor could be defined as the ratio between the maximum current for a wire in a bundle covered by over-shield and the maximum current for a wire in an identical but unshielded bundle, in the same thermal environment.

Let’s call it Ks: “Shielding Derating Factor”:

$$K_s = \frac{I_{\max\_sb}}{I_{\max\_nsb}}$$

The sizing current for fully loaded bundles becomes:

$$I_{BW} = I_{SW} * K(N) * K_S$$

Analysis and Outcomes

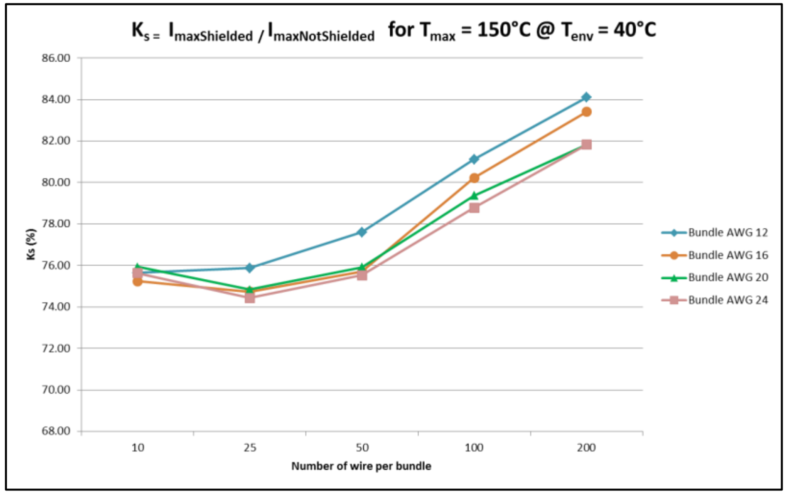
For both the Nickel plated Copper braid and the Aluminium wrapping, the simulation show that:

- The environment temperature (in the simulated range) does not have a significant impact on the Ks factor.
- In line with test results, the Ks factor is higher for bigger bundles: the shielding has less impact on bigger bundle.

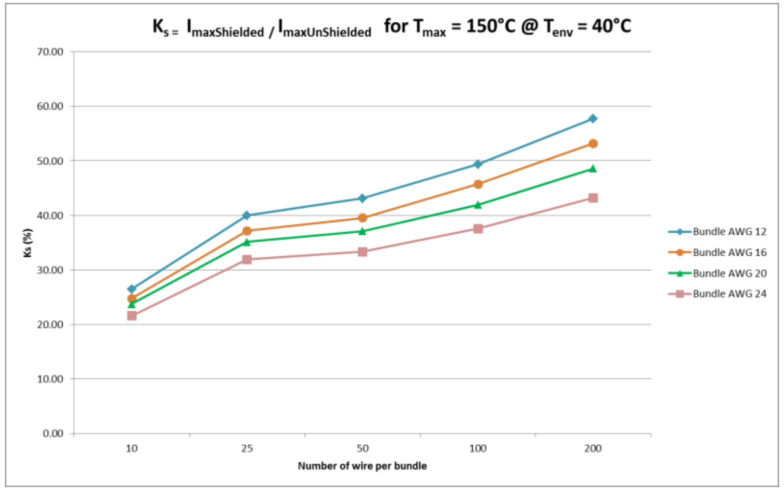
The main differences between the two types of EMI shields are:

- The Ks factor vary significantly depending on the gauge and the number of wires for the Aluminium foil, but not much for the nickel-plated copper braid.
- The value of the Ks factor is higher for the nickel-plated copper than for the Aluminium foil

Nickel-plated Copper:	0.75 < Ks < 0.85
Aluminium foil:	0.2 < Ks < 0.6



Nickel plated Copper braid



Aluminium foil

Shielding Derating Factors Values

The tests and simulations are only covering two types of EMI shields and a limited range of configurations (detailed before).
In that domain, conservative values could be proposed:

Shielding Derating Factor for Nickel-plated copper braid (Federal Mogul Roundit® FMJ sleeve):

Ks = 0,75

Shielding Derating Factor for Aluminium Foil wrapping (Advance Metal International, 20mm width, wrapped tightened, 50% overlap):

Number of wires	Ks
10	0.22
25	0.32
50	0.34
100	0.38
200	0.45

Conclusions

The present study aimed to evaluate effect of bundle EMI over-shield on the ampacity of the wires. Two types of shields have been investigated: a nickel-plated copper braid and an aluminium foil wrapping.

The tests have confirmed that both **over-shields have a very significant impact on the thermal exchanges** and must be taken into account for the sizing of the wires. In correlation with the test results, mathematical models have shown that compared to the unshielded case, the maximum allowable electric current is reduced by 15% to 35% when the bundles are covered with the nickel-plated braid, and reduced by 40% to 80% when covered with one or two layers of aluminium foil. This reduction factor (introduced here as “Bundle Shield Derating Factor) can depend on the size of the bundle and the gauge of the wires, but the main driver appears to be the type of shield, and especially its thermo-optical and conductive properties.
It shall be noted that the tests and the simulations have been mainly focused on a range of environment temperature of 25°C to 100°C as this range is usually driving most of the harness sizing. The extension to very low or very high temperature environment would deserve additional analyses and tests.

The wrapping of PTFE or Polyimide tape over the shield can mitigate but cannot totally cancel the thermal effect of the shield.
Modelling the thermal behavior of the shielded bundles is complex, but very valuable in order to extend the test results and compute the shield derating factors. However, each shielding technology may deserve additional thermal tests to correlate several parameters, and eventually open the door to elaborate a “universal” model.

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